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Multi-peak Gaussian fit applicability to wind speed distribution

Jami Hossain [a,*], Suman Sharma [a], V.V.N. Kishore [b]

[a] WinDForce Management Services Private Limited, Gurgaon 122018, India
[b] The Energy and Resources Institute, New Delhi 110003, India

A R T I C L E   I N F O

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A B S T R A C T

Efforts to harness wind energy on a large scale have gained momentum across the world. By the end of December 2013, a cumulative capacity of more than 300 GW of wind power projects had been installed all over the world. One of the key aspects involved in implementing wind power projects is the analysis of wind speeds distributions observed or recorded and assessment of annual energy output from the wind turbines. The wind speed frequency distribution is generally assumed to follow two-parameter Weibull Distribution. In general, across the world, annual energy generation estimations of a wind turbine at a given site are assessed on the basis of Weibull Distribution. However, in this paper, based on a robust analysis carried out on over 208 measurement sites in India, we show that multi-peak Gaussian distribution functions are a significantly improved representation of observed wind speed distributions.

Contents

1. Introduction

The worldwide installed capacity of wind power was a little more than 300 GW at the end of December 2013 [1]. The electricity generated from these windfarms accounts for more than 3.5% of the global electricity consumption [1]. Geographically, there is now a widespread deployment of modern wind turbine technology across the globe and nearly all the countries are including wind energy in their plans and policies. Over the last 5–10 years, utility-scale wind electricity generation has emerged as a mature mainstream energy technology.

A prerequisite for setting up a windfarm is detailed wind resource assessment at the site, which includes measurement of wind speeds and other climatic conditions for a minimum 3-year period. However, given the pace at which windfarms are being planned and the commensurate speed with which policies, programs and the legal, statutory and regulatory frameworks should

* Corresponding author.
E-mail addresses: jami@windforce-management.com (J. Hossain), suman@windforce-management.com (S. Sharma), vvnk@teri.res.in (V.V.N. Kishore).

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be set in place, the stakeholders and agencies involved are always in a hurry and often try to reduce the development time. An important component in the development time is the wind speed measurement period. Reduction in measurement period can be achieved by means of mathematical modelling of different aspects of wind resource. Some of these aspects are vertical and horizontal extrapolation of wind regimes, regional assessment of large geographical areas, wind distribution modelling, correlations with nearby measurements, etc. With these techniques, it is possible to reduce not only the measurement but also unnecessary expenses.

Here, mathematical modelling of wind speed distributions plays an important role. Assessments of annual energy output (AEO) from wind turbines are often made using mathematical models in which a mathematical function is assumed to represent the actual wind speed frequency distribution. This enables AEO computations to be made by using only a few parameters and the mathematical function mimics the frequency distribution of wind speeds.

Though there are different kinds of functions that could be fitted to wind speeds measured at a site, the two-parameter Weibull distribution has wide acceptance across the world. In spite of scientific improvements, standardization of measurement procedures such as International Electrotechnical Commission (IEC) [2], variance in AEO assessments from actual output of windfarms continues to be an area of major concern in the wind industry. The purpose of the work reported here is to assess the suitability of multi-peak Gaussian function to wind speed distributions in place of Weibull distribution function and to compare the two.

Our analysis with wind speed data from 208 locations, spread all over India, indicates that wind speed distributions have a much better fit with Gaussian multi-peak functions as compared to Weibull distribution.

2. A review of different models

Justus et al. [3] have justified the use of Weibull distribution and its subset, the Rayleigh distribution, which is the Weibull distribution with "$k=2$". Innumerable books and publications [4–7] have used, projected or justified Weibull distribution or Rayleigh distributions as good representation of wind speed distributions. Sedefian [8] has assumed Weibull distribution in his presentation of methods of extrapolating wind distributions to different heights. Pang et al. [9] have reiterated the reasons for using Weibull distribution given by Justus et al. [3]. Pang et al. have estimated three parameters of Weibull distribution using Markov Chain Monte Carlo (MCMC) method and Max Likelihood (ML) methods. They have concluded that for the data analysed by them, there was little evidence that the three-parameter Weibull model was necessary, thus implying that the two-parameter Weibull distribution described above was adequate for approximating wind speed distribution.

Both Lysen and Justus have also mentioned Rayleigh distribution which is a special case of Weibull distribution with $k=2$. The Rayleigh distribution offers additional advantage over Weibull distribution due to the fact that the computations become more simplified as only one variable, i.e., 'mean wind speed', has to be used in the computations. This could have a significant implication on computational time and effort when assessments are being made for a geographical area or at a regional level.

A study on Antarctica has used Rayleigh distribution [10]. In the assessment of California offshore assessment [11] and the Global wind potential assessment also, Rayleigh distribution has been assumed.

In more recent work by Celik and Muneer [12], a critical evaluation of different frequency distributions has been carried out. In addition to two-parameter Weibull and Rayleigh distributions they have also evaluated the applicability of three-parameter Weibull distribution, lognormal distribution and bimodal Weibull distribution. For the data analyzed, they have found bimodal Weibull distribution provides the best fit. However, the shortcoming with this work is that it uses data from only one site and secondly the objective of the paper seems to be development of a method of arriving at a score to figure out which model is best suited to a given wind distribution and not to establish as to which model, in general and for wider applicability, is the appropriate approximation for representing wind speed distributions. Celik [13] assessed the error in energy estimation of small wind power systems using Weibull distribution to be of the order of 2.79%. Kollu et al. [14] have evaluated three mixture probability density functions Weibull-extreme value distribution (GEV), Weibull-lognormal, and GEV-lognormal distributions for their suitability to wind distributions and concluded that mixture distributions are able to provide better fit. Akdag et al. [15] have evaluated two-parameter Weibull distribution and two-component mixture Weibull distribution with five parameters and concluded a mixture of two Weibull distributions is more suitable for the description of such wind conditions and could offer less relative errors in determining the annual mean wind power density.

It is interesting to note that a mixture of distributions turns out to be a better fit than a single Weibull distribution. It is a known fact that wind speed distributions are often multi-modal or bi-modal particularly. Such bi-modal or multipeak distributions will always present difficulties in fitting them to a single Weibull distribution.

With the exception of more recent work of Celik and Muneer [12], Kollu et al. [14] and Akdag et al. [15], who have either carried out a critical evaluation of different frequency distributions w.r.t. wind energy or have attempted mixtures of two or more probability distribution functions, literature search carried out so far continues to point overwhelmingly towards two-parameter Weibull distribution or the Rayleigh distribution as the widely accepted choice for representing wind speed distribution. However, in our analysis presented here, we find that multipeak Gaussian distributions are a significantly better fit than Weibull and Rayleigh distributions.

3. Theory and formulations

3.1. Probability density function

The probability density function (PDF) is a function that can be integrated to obtain the probability of occurrence of the variable having a value in a given class interval. The probability density function is nonnegative everywhere, and its integral over the entire space is equal to one.

A probability density function is most commonly associated with absolutely continuous univariate distributions. A random variable X has density f, where f is a non-negative function [16–18], if

$$P[a \le X \le b] = \int_a^b f(x)dx \quad (1)$$

Hence, if F is the cumulative distribution function of "x", then

$$F(x) = \int_{-\infty}^{x} f(u)du \quad (2)$$

and (if f is continuous at "x")

$$f(x) = \frac{d}{dx}F(x) \tag{3}$$

Intuitively, one can think of $f(x)\,dx$ as being the probability of "x" falling within the infinitesimal interval $[x, x+dx]$.

3.2. Normal distribution

A random variable which has a normal distribution with a mean $m=0$ and a standard deviation $\sigma=1$ is referred to as Standard Normal Distribution.

3.3. Weibull distribution

The Weibull distribution is widely used in engineering and scientific analysis. It is used in survival, reliability and failure analysis, manufacturing and delivery times, extreme value theory and weather forecasting. In wind energy, it is a well-established fact that a wind speed frequency distribution can be approximated by a Weibull distribution [19], which is described by shape parameter "k" and scale parameter "c". Rayleigh distribution, a special case of Weibull distribution with $k=2$, is also widely used to represent wind distributions.

The Weibull probability density function (PDF) for wind speed "v" is given by

$$f(v) = (k/c)\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{4}$$

In the above $(k>0,\ v>0,\ c>1)$.

The relationship between scale parameter "c", shape parameter "k" and mean wind speed "v_m" is given by

$$v_m = c\Gamma\,(1 + k^{-1}) \tag{5}$$

where "Γ" is the Gamma function.

The energy output from the wind turbine over time period "T" is given by

$$E = T\int_{V_{in}}^{V_r} P(V)f(v)dv + T\,Pr\int_{V_r}^{V_{out}} f(v)dv \tag{6}$$

where "$P(V)$" is the power curve function of the wind turbine, "Pr" is its rated power, "v_{in}" is the cut-in wind speed, "v_r" is the rated wind speed and "v_{out}" is the cut-out wind speed and "$f(v)$" is given by Eq. (4). A form of Eq. (6) shown in Eq. (7) can be used to compute annual energy output (AEO) from a given wind turbine:

$$AEO = 8760\sum_{i}^{N} P_i V_i \tag{7}$$

In Eq. (7), "V_i" is the frequency for different wind speed class intervals of a wind speed frequency distribution that can be derived from Eq. (4) for frequency distributions with different "k" and "c" and "V_m", n is the number of class intervals and "P_i" is the value of power generated corresponding to the mid value of the ith class interval and is obtained from the wind turbine power curve, $P(V)$.

3.4. Gaussian distribution

Apart from fitting Weibull and Rayleigh distributions to the percent frequency distributions, we also fitted Gaussian distribution. A Gaussian distribution is given by

$$g(x) = ae^{-(x-b)^2/2c^2} \tag{8}$$

where a, b, and c are the curve parameters that control the shape of the function. 'a' is the height of the curve at the maximum, 'b' is the value of 'x' where the maximum occurs, and 'c' controls the width of the curve, that is, how rapidly it falls to zero. To use the Gaussian as a probability distribution function, we require that the total area under the curve equals one. The normalized Gaussian distribution function is given by

$$G(x) = \frac{1}{\sigma\sqrt{2\pi}}e^{-(x-\mu)^2/2\sigma^2} \tag{9}$$

The curve fitting software ORIGIN 9 (www.originlab.com) enables such a curve fitting over the graph plotted on its graphing tool.

Goshtasby and O'Neill [21] have shown that a sequence of uniformly spaced points $\{x_i: i=1,\ldots,N\}$ with associated data values $\{y_k: k=1,\ldots,N\}$ can be approximated by a sum of Gaussians in the form

$$y = f(x) = \sum_{i=1}^{n} A_i e^{-(x-x_i)^{2}/2\sigma_i^2} \tag{10}$$

After fitting the wind speed frequency distribution to Gaussian functions as in Eq. (10), AEO can be computed by Eq. (7) as was done in the case of Weibull distribution.

3.5. R-squared value

The R-squared value, a measure of goodness of fit used to compare the results of fitting different types of distributions to the actual distribution, is given by

$$R = 1 - \frac{SSE}{SST} \tag{11}$$

where SSE, also known as summed square of residuals, is given by

$$SSE = \sum_{1}^{N}(x_i - y_i)^2 \tag{12}$$

where "x_i" are the actual or observed frequency distribution values for N class intervals and "y_i" is the predicted value (in this case through the Gaussian fit).

SST is the total sum of squares given by

$$SST = \sum_{1}^{N}(x_i - \mu)^2 \tag{13}$$

4. Data and analysis

In order to compare suitability of multi-peak Gaussian distribution with Weibull and Rayleigh distribution, we carried out analysis with data measured at 208 sites in India. The locations of these measurement sites are shown in the map in Fig. 1. The data has been measured, analysed and published by CWET. The publications by CWET present percentage frequency distribution, shape parameter k, scale parameter c, mean annual wind speeds at different heights and air density.

These measurements are being carried out under a National Program of the Ministry of New and Renewable Energy (MNRE) that involves setting up wind masts at varying heights. Till date nearly 2080 [22] wind measurement masts at 20 m, 25 m and 50 m have been set up and the data is being periodically published by the Chennai-based Centre for Wind Energy Technologies (CWET), which is the scientific wing of MNRE. The first compilation [23] was published in 1983. Over the years, such publications [24–31] have continued to provide updated processed information on wind speeds in India.

Under this programme, all the wind monitoring stations are equipped with identical instrumentation. Each installation consists of a 20/25 m tall, 75 mm diameter, guyed tubular steel mast with booms fixed at two levels 10 m and 20/25 m above ground and a wind resource data logging system. Now wind masts with height up to 120 m above the ground are also being set up. Data is

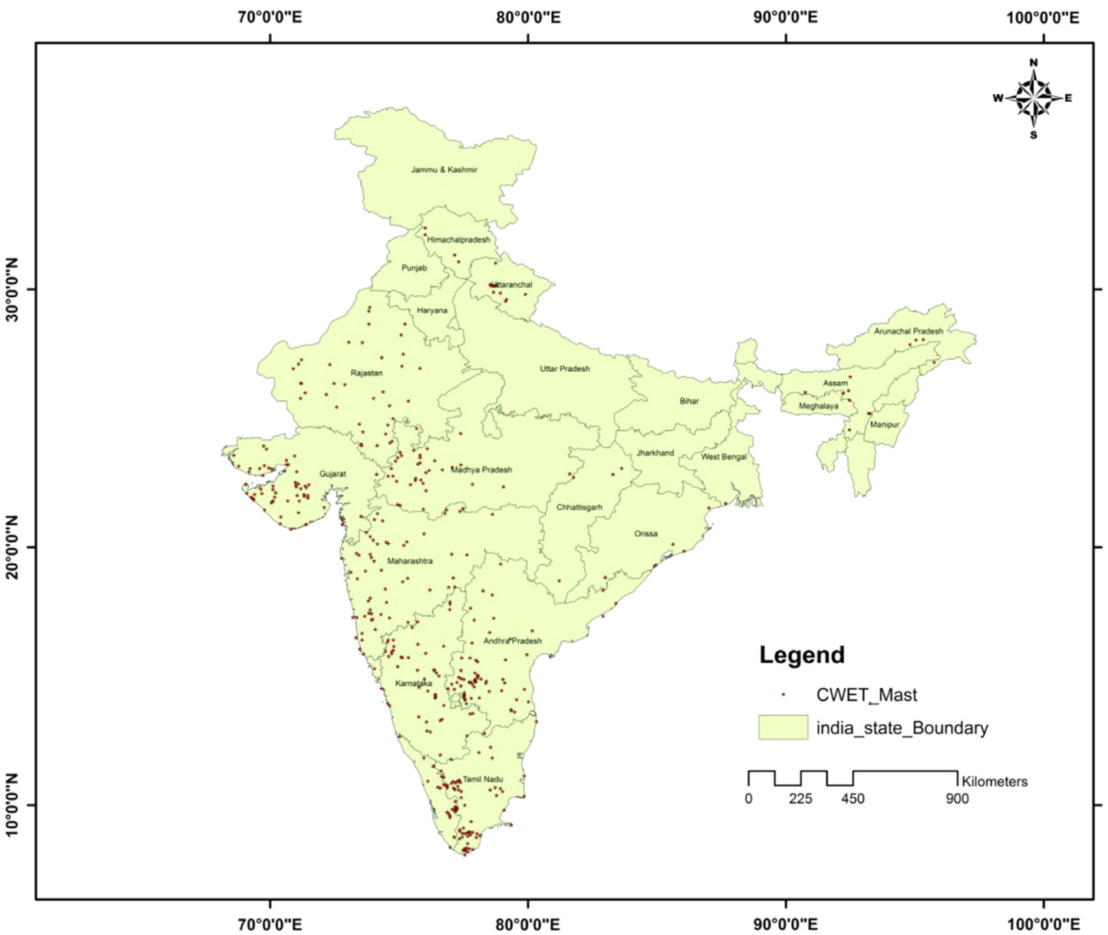

Fig. 1. Overview of analysed sites (208) location on Indian map published by Centre of Wind Energy Technology (CWET), Chennai.

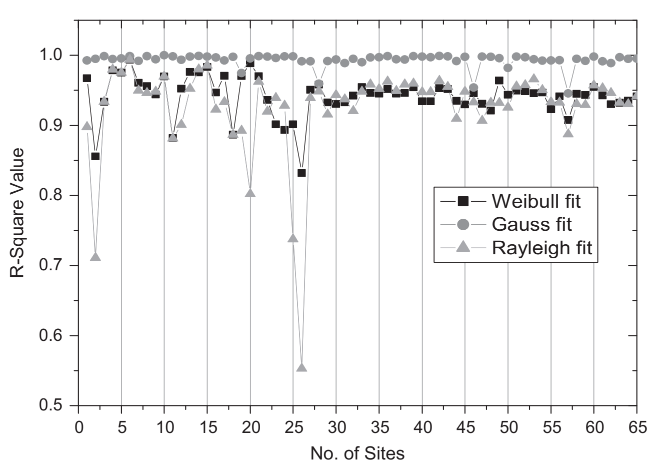

Fig. 2. Comparisons of R-square value of 65 sites based on Weibull, Rayleigh and Gaussian distribution fit.

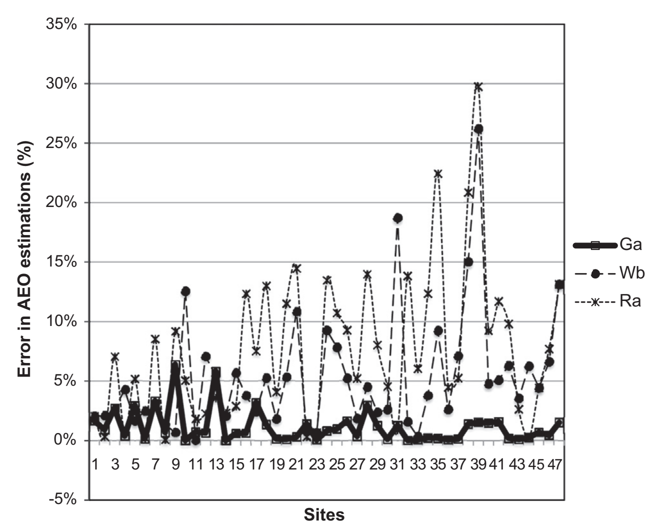

Fig. 3. Error in AEO estimations based on actual in comparison with Gauss, Weibull and Rayleigh distribution functions.

sampled at a frequency of 0.5 Hz (2 s) and averaged over one hour. The data loggers are set to store the wind speed in 'm/s' (meter-per-second), wind direction and standard deviation of wind speed at two levels. In order to ensure that data collected is both reliable and accurate, the installation, maintenance and periodic inspection of the instruments and the collection of chips have been carried out by CWET under rigidly controlled conditions.

We have used percentage frequency distribution, shape parameter k, scale parameter c and mean annual wind speeds from the above publications [17, 21–28] for the 208 sites spread all over the country. The percentage frequency distribution presented in these publications is treated as the actual wind speed distribution at the site and then the R-squared (R^2) values, that are a measure of the goodness of fit, have been computed for fitting three different distribution functions to actual wind speed distribution, i.e.,

- Weibull
- Rayleigh
- Multi-peak Gaussian

We have also computed annual energy output (AEO) from a given wind turbine (Suzlon S-88) for these sites to study the sensitivity of AEO with respect to the frequency distributions assessed and also to assess the error in estimation in comparison with the assessment made with actual frequency distribution. The *R*-squared values between actual measurement for these sites (percent frequency distribution) and the multi-peak Gauss, Rayleigh and Weibull distributions are presented in Fig. 2 (for better visibility 65 sites are presented). The Mean Absolute Error in AEO computations when compared with AEO computations from actual distribution were found to be 4% with Gauss, 6% with Weibull and 8% with Rayleigh distribution. The plot of error in AEO estimation for a dataset comprising 47 sites in Fig. 3 shows that Gaussian multi-peak distribution results in minimum error in energy estimations.

5. Results and discussion

It can be seen from Eq. (7) that AEO computations are sensitive to the kind of distribution assumed for wind speeds.

Fig. 4 presents percentage frequency wind speed data in decimals at one of the sites out of the 208 sites in *Karnataka State*

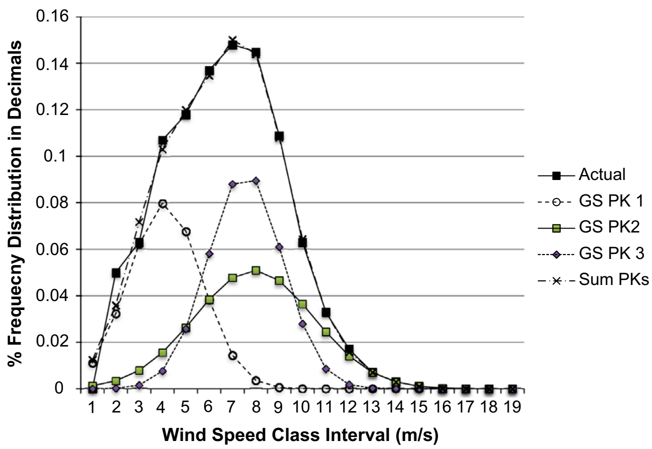

Fig. 4. General representation of percent frequency wind speed distribution function.

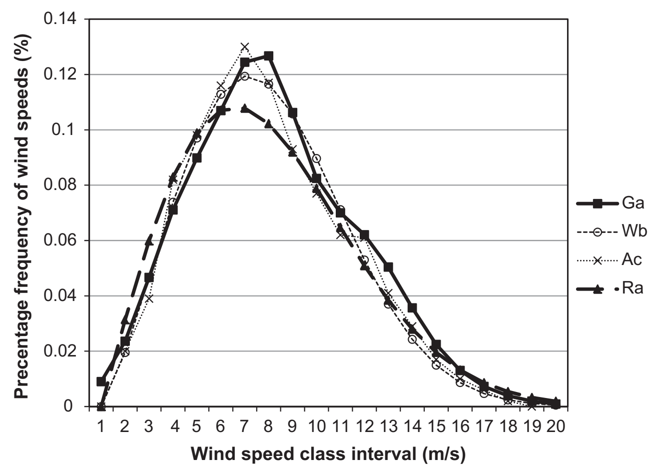

Fig. 5. A comparison of different frequency distribution functions (site: Kapattagudda).

Table 1
R^2 value computation using Gaussian distribution function at *Channavadayanpura* using multi-peak technique for curve fitting.

Site: Channavadayanpura							
Mean wind speed: 6.3							
Weibull shape factor *k*: 2.4							
					Guass-Actual fit		
Output from ORIGIN on Gaussian fit (Fig. 5)					SSE (Actual-Guass)	0.000463	
	Area (*A*)	**Mean (*xc*)**	**Width (*w*)**		SSE (Actual-Guass)	0.058090	
Peak 1	0.31349	3.10299	3.12733		SSE/SST	0.007964	
Peak 2	3.25	6.91794	5.09		*R*–squared	0.992036	
Peak 3	0.3704	6.54123	3.16709				
Wind speed (m/s)	Actual % Freq distribution	Guass distributions			Guass peaks summed	SSE calc.	SST calc.
	Actual	GS PK 1	GS PK 2	GS PK 3	Sum PKs		
0.00	0	0.011165	0.001266	0.000018	0.012450	0.000155	0.002776
1.00	0.05	0.032376	0.003410	0.000205	0.035991	0.000196	0.000007
2.00	0.063	0.062365	0.007874	0.001528	0.071767	0.000077	0.000106
3.00	0.107	0.079808	0.015576	0.007656	0.013041	0.000016	0.002950
4.00	0.118	0.067847	0.026405	0.025747	0.120000	0.000004	0.004266
5.00	0.137	0.038317	0.038358	0.058110	0.134785	0.000005	0.007109
6.00	0.148	0.014376	0.047747	0.088021	0.150144	0.000005	0.009085
7.00	0.145	0.003583	0.050931	0.089480	0.143994	0.000001	0.008522
8.00	0.109	0.000593	0.046555	0.061049	0.108194	0.000001	0.003171
9.00	0.063	0.000065	0.036462	0.027953	0.064481	0.000002	0.001060
10.00	0.033	0.000005	0.024472	0.008590	0.033067	0.000000	0.003870
11.00	0.017	0.000000	0.014075	0.001772	0.015847	0.000001	0.001273
12.00	0.007	0.000000	0.006936	0.000245	0.007182	0.000000	0.002087
13.00	0.003	0.000000	0.002929	0.000023	0.002952	0.000000	0.002469
14.00	0.001	0.000000	0.001060	0.000001	0.001061	0.000000	0.002671
15.00	0	0.000000	0.003290	0.000000	0.000329	0.000000	0.002776
16.00	0	0.000000	0.000087	0.000000	0.000087	0.000000	0.002776
17.00	0	0.000000	0.000020	0.000000	0.000020	0.000000	0.002776
18.00	0	0.000000	0.000004	0.000000	0.000004	0.000000	0.002776
Mean	0.052684						

Table 2
R^2 value computation using Weibull and Rayleigh distribution function at *Channavadayanpura* on multi-peak wind speed distribution.

Site: Channavadayanpura							
Mean wind speed: 6.3 m/s							
		SST (Actual-WEIBULL)	0.0032		SST (Actual-Rayleigh)	0.005415	
		SST (Actual-WEIBULL)	0.0581		SST (Actual-Rayleigh)	0.058090	
		SSE/SST	0.0550		SSE/SST	0.093225	
		R-squared	0.9450		*R*-squared	0.906775	
Wind speed (m/s)	Actual % freq distribution	Weibull	SSE calc.	SST calc.	Rayleigh	SSE calc.	SST calc.
0.00	0	0.0000	0.0000	0.0028	0.0000	0.0000	0.0028
1.00	0.05	0.0215	0.0008	0.0000	0.0388	0.0001	0.0000
2.00	0.063	0.0546	0.0001	0.0001	0.0732	0.0001	0.0001
3.00	0.107	0.0891	0.0003	0.0030	0.0995	0.0001	0.0030
4.00	0.118	0.1175	0.0000	0.0043	0.1154	0.0000	0.0043
5.00	0.137	0.1343	0.0000	0.0071	0.1207	0.0003	0.0071
6.00	0.148	0.1369	0.0001	0.0091	0.1165	0.0010	0.0091
7.00	0.145	0.1261	0.0004	0.0085	0.1051	0.0016	0.0085
8.00	0.109	0.1055	0.0000	0.0032	0.0892	0.0004	0.0032
9.00	0.063	0.0806	0.0003	0.0001	0.0717	0.0001	0.0001
10.00	0.033	0.0562	0.0005	0.0004	0.0546	0.0005	0.0040
11.00	0.017	0.0358	0.0004	0.0013	0.0397	0.0004	0.0013
12.00	0.007	0.0209	0.0002	0.0021	0.0274	0.0002	0.0021
13.00	0.003	0.0111	0.0001	0.0025	0.0181	0.0001	0.0025
14.00	0.001	0.0054	0.0001	0.0028	0.0114	0.0000	0.0027
15.00	0	0.0024	0.0000	0.0028	0.0069	0.0000	0.0028
16.00	0	0.0009	0.0000	0.0028	0.0040	0.0000	0.0028
17.00	0	0.0003	0.0000	0.0022	0.0022	0.0000	0.0028
18.00	0	0.0001	0.0000	0.0012	0.0012	0.0000	0.0028

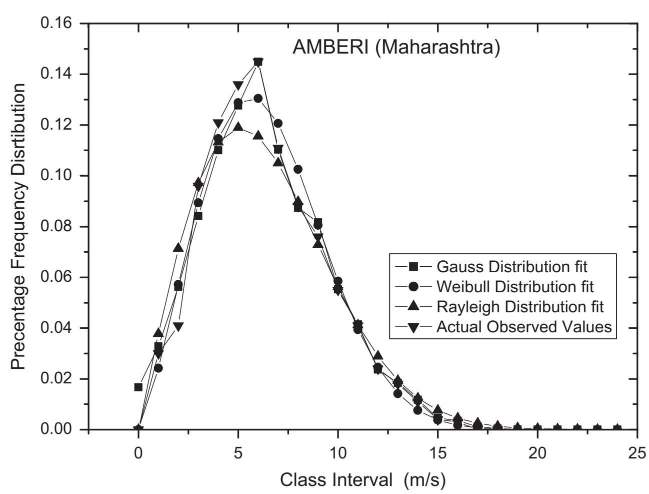

Fig. 6. Modelled (Weibull, Rayleigh and Gaussian distributions) fit for observed data values of percentage frequency distribution of wind speed (m/s) averaged hourly at Amberi (Maharashtra).

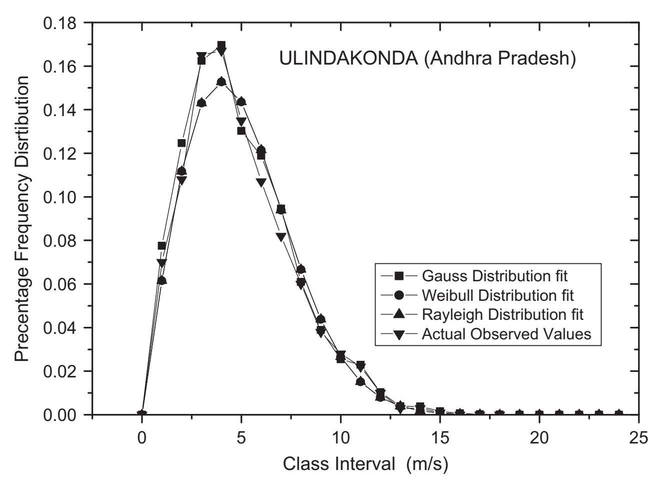

Fig. 7. Modelled (Weibull, Rayleigh and Gaussian distributions) fit for observed data values of percentage frequency distribution of wind speed (m/s) averaged hourly at Ulindakonda (Andhra Pradesh).

– *Channavadayanpura in coastal Karnataka*. We have used percent frequency data (which represents actual distribution) and Weibull shape parameter values for 208 sites in our analysis. Table 1 presents the R^2 value which has been computed at *Channavadayanpura* using multi-peak Gaussian distribution function technique for curve fitting.

A comparison of the three different distributions with actual percentage frequency distribution at a site *Kapattaguda* is shown in Fig. 5.

A vast study of percentage frequency distribution of wind speed data has been carried out and different types of peaking in the distributions have been observed, e.g. uni-mode, bi-mode and multi-mode. We have tried to fit these distributions with Weibull, Rayleigh and Gaussian distribution functions and compared the best fit results. Table 2 presents the R^2 values that have been computed at *Channavadayanpura* using Weibull and Rayleigh distribution functions. In this research paper R^2 values are used to compare the best fit model with actual wind speed data.

In order to show our results in pictorial view two sites have been selected for each peak mode.

5.1. Uni-mode curve

At Amberi (Maharashtra) and Ulindakonda (Andhra Pradesh) wind speed distribution is uni-modal as shown in Figs. 6 and 7, respectively. In both Figs. 6 and 7, Weibull, Rayleigh and Gauss distributions show approximately similar R^2 values varying from

0.95 to 0.99. The R^2 value is closer to "1.0" in Gaussian fit probability distribution. The high value of R^2 shows good relationship between observed and modelled values.

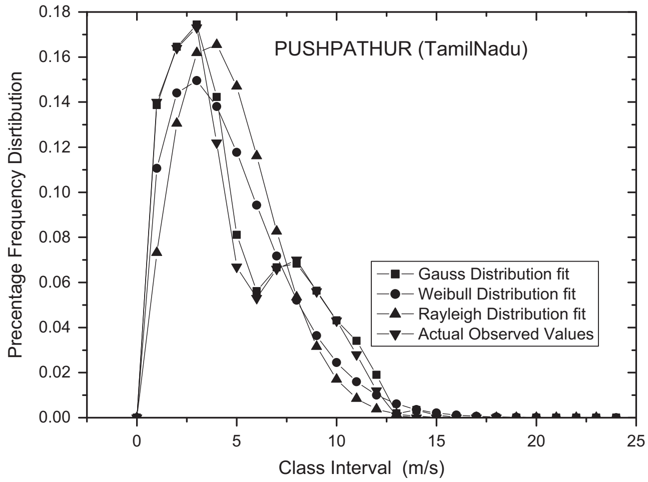

Fig. 8. Modelled (Weibull, Rayleigh and Gaussian distributions) fit for observed data values of percentage frequency distribution of wind speed (m/s) averaged hourly at Pushpathur (Tamil Nadu).

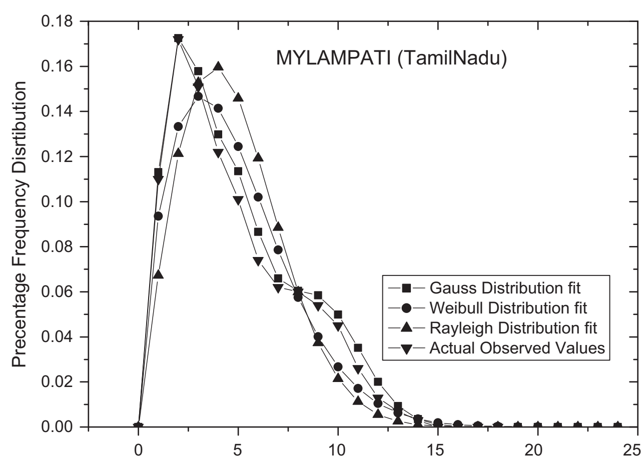

Fig. 9. Modelled (Weibull, Rayleigh and Gaussian distributions) fit for observed data values of percentage frequency distribution of wind speed (m/s) averaged hourly at Mylampati (Tamil Nadu).

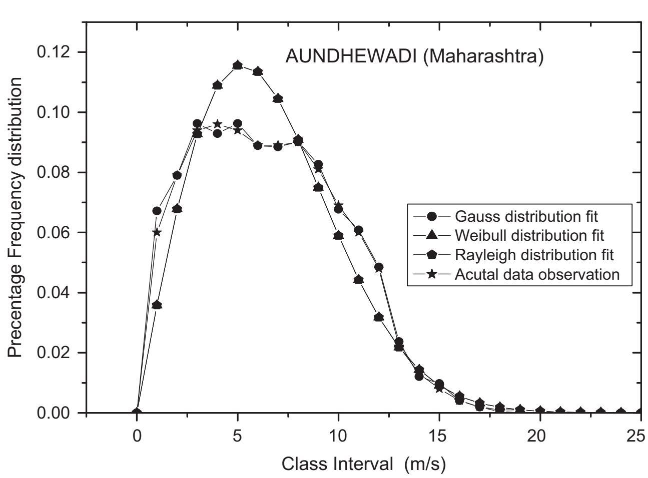

Fig. 10. Modelled (Weibull, Rayleigh and Gaussian distributions) fit for observed data values of percentage frequency distribution of wind speed (m/s) averaged hourly at Aundhewadi (Maharashtra).

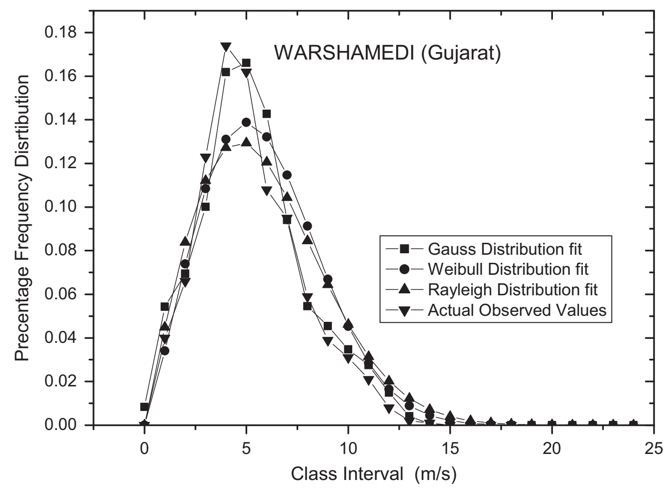

Fig. 11. Modelled (Weibull, Rayleigh and Gaussian distributions) fit for observed data values of percentage frequency distribution of wind speed (m/s) averaged hourly at Warshamadi (Gujarat).

5.2. *Bi-mode and multi-mode curve*

Pushpathur (Tamil Nadu) and Mylampati (Tamil Nadu) sites have been selected for bi-modal (two prominent peaks) illustration in Figs. 8 and 9 respectively. Here we see that while the R^2 value is close to 1 in case of Gauss function, it is much lesser in case of Weibull and Rayleigh distribution functions. We find a similar result, in multi-modal (more than two prominent peaks) illustration in Figs. 10 and 11 for Aundhewadi (Maharashtra) and Warshamedi (Gujarat) sites, respectively. This exercise has been carried out over 208 measurement sites.

Bi-modal and multi-modal curve fitting with Weibull, Rayleigh and Gauss frequency distribution functions has been compared. The R^2 value is found to be significantly higher for Gaussian fit when compared with Weibull and Rayleigh distribution functions.

In wind resource assessment, determination of accurate annual energy output (AEO) is of great importance. Since the AEO determination is linked to distribution curve fit, it requires careful treatment in analysis and estimation. We feel that the most important finding from our work reported here is the greater suitability of Gaussian Multi Peak functions as compared to Weibull and Rayleigh functions to a wide range of wind speed datasets, covering almost the whole of India. Given the size of our dataset, we can claim that this finding is indeed universally applicable.

6. Conclusions

Our main finding is that the wind distribution function is better approximated by multi-peak Gaussian curves in comparison with customarily assumed Weibull and Rayleigh distribution functions. This finding is based on analysis carried out with measurements at 208 sites with varying wind regimes throughout the Indian subcontinent. The approach of AEO assessment as presented in the study using multi-peak Gaussian function can be efficiently and effectively adopted for greater accuracy. The robustness of datasets and the findings reveal that the phenomenon is universally applicable.

There is worldwide growth and expansion in the deployment of wind energy technologies and in this process accuracy in assessments of AEO from measured or assessed data is of immense importance. Worldwide, wind industry is trying to cope with variance in AEO assessments from the actual generation achieved.

This variance can be reduced, to a significant extent, by paying greater attention to the frequency distribution models assumed in the analysis.

Therefore, we recommend that this exercise should be carried out for wind speed data in other parts of the world and additional formulations established for undertaking different kinds of analysis with wind speeds, height extrapolation, wind turbine design considerations and energy assessments.

References

[1] ⟨http://www.wwindea.org/webimages/Half-year_report_2013.pdf⟩ [accessed 21.12.13].
[2] ⟨http://www.iec.ch/renewables/wind_power.htm⟩.
[3] Justus CG, Hargraves WR, Mikhail Amir, Graber Denise. Methods for estimating wind speed frequency distributions. J Appl Meteorol 1978;17:350–3.
[4] Manwell James F, McGowan Jon G, Rogers Anthony L. Wind energy explained: theory, design and application. John Wiley & Sons; 2010; 740.
[5] Lysen EH. Introduction to wind energy. The Netherlands: SWD; 1982.
[6] Kishore VVN. Renewable energy engineering & technology: a knowledge compendium. New Delhi: Teri Press; 2008; 445–501 (ISBN 81-7993-093-9).
[7] Hossain J, Vinay Sinha, Kishore VVN. A GIS based assessment of potential for windfarms in India. Renew Energy 2011;36(12):3257–67, http://dx.doi.org/10.1016/j.renene.2011.04.017.
[8] Sedefian Leon. On the extrapolation of mean wind power density. J Appl Meteorol 1979;19:488–93.
[9] Pang Wan-Kai, Forster Jonathan J, Troutt Marvin D. Estimation of wind speed distribution using Markov chain Monte Carlo techniques. J Appl Meteorol 2001;40:1476–84.
[10] Hossain J. Estimation of Specific annual energy generation from wind in Antarctica. Sol Wind Technol 1989;6(1):91–5.
[11] Dvorak Michael J, Archer Cristina L, Jacobson Mark Z. California offshore wind energy potential. Renew Energy 2010;35:1244–54.
[12] Celik N, Makkawi A, Muneer T. Critical evaluation of wind speed frequency distribution functions. J Renew Sustain Energy 2010;2:013102, http://dx.doi.org/10.1063/1.3294127.
[13] Celik Ali Naci. Energy output estimation for small-scale wind power generators using Weibull-representative wind data. J Wind Eng Ind Aerodyn0167-6105 2003;91(5):693–707.
[14] Kollu Ravindra, Rayapudi Srinivasa Rao, Narasimham SVL, Pakkurthi Krishna Mohan. Mixture probability distribution functions to model wind speed distributions. Int J Energy Environ Eng 2012;3:27, http://dx.doi.org/10.1186/2251-6832-3-27.
[15] Akdağ SA, Bagiorgas HS, Mihalakakou G. Use of two-component Weibull mixtures in the analysis of wind speed in the Eastern Mediterranean. Appl Energy 2010;87(8):2566–73.
[16] Evans M, Hastings N, Peacock B. Probability density function and probability function. §2.4 in statistical distribution. 3rd ed.. New York: Wiley; 2000; 9–11.
[17] Kendall MG, Stuart A. The advanced theory of statistics. Vol. 3, 2nd ed. New York: Hafner Publishing Company; 1968.
[18] Patel Jagdish K, Read Campbell B. Handbook of the normal distribution. CRC Press; 1996. ISBN: 0824715411.
[19] ⟨http://www.weibull.com⟩.
[21] Ardeshir Goshtasby, William D O'Neill. Curve fitting by a sum of Gaussians. Graph Models Image Process 1994;56(4):281–8pp 1994;56:281–8.
[22] Centre for Wind Energy Technology. List of wind monitoring stations with MAWS & MAWPD (MNRE as on 30.11.10), ⟨http://www.cwet.tn.nic.in/html/departments_wms.html⟩ [accessed 05.01.11].
[23] Mani A, Mooley DA. Wind speed data over India. New Delhi: Allied Publishers; 1983.
[24] Mani A. Wind energy resources survey for India-I. New Delhi: Allied Publishers; 81-7023-297-X1990; 347.
[25] Mani A. Wind energy resources survey for India-II. New Delhi: Allied Publishers; 81-7023-358-51992; 591.
[26] Mani A. Wind energy resources survey for India-III. New Delhi: Allied Publishers; 81-7023-221-X1994; 637.
[27] Mani A, Rangarajan S. Wind energy resources survey for India-V. New Delhi: Allied Publishers; 1996; 518.
[28] Rangarajan S. Wind energy resource survey in India-V. Bangalore: Ministry of Non-conventional Energy Sources; 1998.
[29] Rangarajan S. Wind energy resources survey for India-VII. Chennai: C-WET; 2005; 427.
[30] Wind energy: resource survey in India-VI, 2001, Centre for Wind Energy Technologies, Chennai.
[31] Directory, Indian windpower-2011, vol. I. Bhopal: Consolidated Energy Consultants; 2011.